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Moisture penetration in oak during sinusoidal humidity fluctuations studied by NMR

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HIGHLIGHTS

- Experimental study on moisture penetration in oak using NMR.
- One-dimensional transport during sinusoidal humidity fluctuations.
- Different principal transport directions have different transport characteristics.
- Moisture transport described by diffusion equation with surface resistance.
- Influence of humidity range minor on transport behavior.

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ABSTRACT

Most natural fluctuations in relative humidity are cyclic of nature, e.g. daily or seasonal. During these fluctuations, hygroscopic materials exchange moisture with the surrounding air. The penetration of moisture into the material depends on the frequency of the fluctuation, but also on the transport characteristics of the material. Here we present an experimental study on the penetration depth of moisture in oak during sinusoidal relative humidity fluctuations, covering a wide range of frequencies. Using nuclear magnetic resonance, we show that the amplitude in moisture content decreases exponentially from the exposed surface. The slope of the decay on a logarithmic scale provides the diffusion coefficient in the three principal directions of wood (longitudinal, radial, tangential), which are in good agreement with literature values. Furthermore, we show the influence of the moisture content range on the decay in amplitude by performing experiments in different relative humidity ranges. Numerical experiments are performed to assess the dependence of moisture penetration on different model parameters.

1. Introduction

A wide variety of wooden objects in the built environment is exposed to a fluctuating climate, e.g. furniture, construction elements in housing, but also works of art. A change in the ambient relative humidity results in moisture exchange between wood and air. As a consequence, the moisture content of the wood changes continuously. This can be advantageous since it contributes to the moisture buffering capacity of a room, ensuring a more stable indoor climate, affecting comfort but also energy consumption [1]. The buffering capacity of building materials has accordingly been subject of several studies [2–4], e.g. for application in building energy simulation [5–7]. Since the buffering capacity is governed by moisture transport, it is important to characterize transport behavior.

The penetration of moisture in wood has been studied extensively for step changes in the ambient relative humidity, including drying [8–12]. These conditions are, however, rare in the built environment; changes in relative humidity of indoor climates are most often cyclic. An example of a fluctuation in indoor relative humidity is shown in Fig. 1a for the grosse Galerie at Schönbrunn palace in Vienna, Austria. The cyclicality of the fluctuations is already apparent from the time-domain data, elucidated by the frequency spectrum after Fourier transform in Fig. 1b. Peaks at dominant fluctuations of one day and one year are immediately visible. Typical relative humidity fluctuations can thus be decomposed into a sum of sinusoidal fluctuations with different frequencies and amplitudes. The penetration of moisture into the material is dependent on the frequency of the external changes and the transport properties of the material [13,14]. Moisture will penetrate

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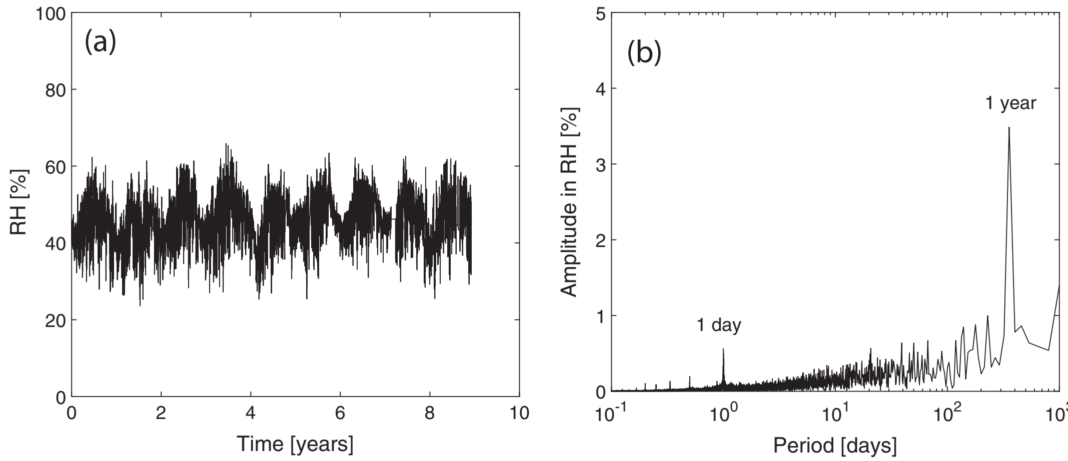

Fig. 1. (a) The time-evolution of the relative humidity in the grosse Galerie at Schönbrunn palace in Vienna, Austria, over the course of nine years (http://www.monumenten.bwk.tue.nl/). (b) The frequency spectrum after Fourier transform, clearly showing peaks at dominant fluctuation frequencies.

further into the material when exposed to slow fluctuations. Furthermore, at the same fluctuation frequency, the penetration depth will be higher for a material which is more permeable to moisture.

The goal of this study is to investigate the penetration of moisture in oak during relative humidity fluctuations by nuclear magnetic resonance (NMR). This method has been applied before to study the moisture penetration in pine wood during daily alternating step changes in the relative humidity [15]. We intend to study a wider range of sinusoidal fluctuation frequencies to characterize the frequency dependence of moisture penetration in the different principal directions in oak. To this end, we first briefly introduce simple theory based on the diffusion equation. Experiments are then performed using NMR, in which the moisture content profile can be determined non-destructively during sinusoidal relative humidity fluctuations at various frequencies and different relative humidity ranges. The influence of the transport direction on the penetration depth is assessed by doing experiments in the different principal directions of the wood (longitudinal, radial, and tangential). Furthermore, the behavior in different moisture content regimes is explored. Results are discussed and compared to numerical calculations with a moisture-content dependent diffusion coefficient and an alternative moisture transport model. Finally, conclusions are drawn and an outlook is presented.

2. Theory

Many models have been proposed in the literature to describe moisture transport in wood, with a wide range of complexity. In this section, moisture transport in a wooden cylinder with a thickness d will be treated. One surface is exposed to sinusoidal fluctuations in relative humidity, the back surface and side surface are sealed, resulting in one-dimensional moisture transport. Presuming a linear sorption isotherm and no surface resistance, this translates into a sinusoidal fluctuation in moisture content at the exposed surface. Regardless of the driving potential, transport in the material can be described by the diffusion equation [16]. Mathematically, transport can be described by

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right), \tag{1}$$

where c is the moisture content, t time, D the diffusion coefficient, and x the distance from the exposed surface. Here, we will assume a constant diffusion coefficient D to arrive at an analytical expression for the moisture content. Initial and boundary conditions can be formulated as

$$\begin{aligned} &c(x,0) = c_i, \\ &c(0,t) = c_i + A_0\sin(2\pi ft), \\ &\frac{\partial c}{\partial x}(d,t) = 0, \end{aligned} \tag{2}$$

where c_i is the initial uniform moisture content, A_0 the amplitude in moisture content at the exposed surface, f the frequency of the relative humidity changes, and d the sample thickness. In the case of small penetration depths, i.e. in conditions for which the medium can be considered semi-infinite, the moisture content over time can be described analytically by [13]:

$$c(x,t) = c_i + A_0 e^{-kx}\sin(2\pi ft - kx), \tag{3}$$

with k the reciprocal of the penetration depth:

$$k = \sqrt{\frac{\pi f}{D}}. \tag{4}$$

Eq. (3) shows that the fluctuation in moisture content has a phase lag of kx, and the amplitude A at a distance x decays with e^{-kx} away from the exposed surface:

$$A(x) = A_0 e^{-kx}. \tag{5}$$

Rewriting terms in Eq. (5) and using Eq. (4) yields

$$\ln\left(\frac{A}{A_0}\right) = -\sqrt{\frac{\pi}{D}}x\sqrt{f}. \tag{6}$$

If moisture transport in the material can be described by the diffusion equation, the decay in amplitude should be linear on a logarithmic scale, when plotted versus the parameter $x\sqrt{f}$. The slope of the amplitude decay then directly provides the diffusion coefficient.

In the experiments, a finite sample is used. The theory will therefore only hold in case the penetration of the moisture is considerably smaller than the thickness of the sample. Here we numerically assess the influence of sample finiteness on amplitude decay at different frequencies. To this end, we introduce dimensionless parameters, indicated by asterisk superscripts:

$$c^* = \frac{c - c_i}{A_0},\ t^* = \frac{Dt}{d^2},\ x^* = \frac{x}{d},\ f^* = \frac{d^2 f}{D}. \tag{7}$$